Design and Development of Weak Coherent Pulse Source for Quantum Key Distribution System

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***Abstract*—Single photon source is indispensable for realization of photon based quantum communication technologies such as quantum key distribution (QKD). Weak coherent pulse source is a practical, efficient and robust solution to generate stream of single photons, probabilistically. In this paper, a methodology for design and development of weak coherent pulse (WCP) source with high count rate of upto 10 *Mcps* is proposed and implemented. The generation of optical pulses with narrow pulse width and repetition rate of up to 100 *MHz* is achieved by developing a miniaturized pulse laser module. The weak coherent pulses are generated by heavily attenuating the laser pulses so as to reach the mean photon no. per pulse, μ, close to 0.1. WCP source performance in terms of mean photon number, second order coherence and photon count rate is also investigated. The measured $g^{(2)}[0]$ of ~0.98 shows that the developed WCP source has a very good quality.**

***Keywords*—Quantum key distribution (QKD), weak coherent pulses (WCP), single photon source.**

I. Introduction

Recent advancements in technologies like quantum computing and quantum information processing creates threat on security of information transferred over classical communication channel [1]. Quantum cryptography protocols ensures the security of information by exploiting the benefits of quantum Physics principles. High quality single photon source is a critical element in realization of many quantum cryptographic protocols. The security of such protocols is governed by the quality of the single photon emission. The multi-photon pulses must be avoided in QKD systems, due to the possibility of eavesdropping through a photon-number splitting (PNS) attack [2]. An ideal single photon source generates single photon with 100% probability and multi photon or vacuum state with 0% probability. There are many candidates which can be realized as single photon source such as single atoms, ions, molecules and solid state emitters like quantum dots, color centers, carbon nanotubes [3] etc.

Despite much experimental efforts, it is still a challenge to build an efficient, reliable and perfect single photon source [4]. However, photon source based on weak coherent pulses is practically a viable solution for non-ideal single photon source. It finds its applications in many emerging quantum technologies [5][6] etc. It has got significant attention due to its efficient, reliable and robust nature. Weak coherent pulse source can be developed with limited resources and is less complex as compared to ideal single photon sources. This source involves laser module which is able to generate narrow optical pulses with tunable pulse width. The laser pulses are attenuated using appropriate neutral density filters such that each optical pulse contains single photon on average.

Regardless of its wide usage, the design approach of WCP source is not properly reported. In this paper, we present a design and development methodology for the generation of polarized single photon streams. This is based on weak coherent pulses generated by heavily attenuating the laser pulses so as to reach the mean photon per pulse close to 0.1. The WCP source consists of pulse laser module and optical elements. The detailed design methodology for pulsed laser module is also presented, capable of generating optical pulses at a repetition rate of up to 100*MHz* with pulse width as narrow as 5 *ns*. This developed source is experimentally characterized by performing Hanbury-Brown-Twiss (HBT) experiment. The quality of the WCP source is validated by calculating second order coherence. The measured $g^2[0]$ value of ~0.98 shows that the developed WCP source exhibit Poissionian characteristic with very good quality.

This paper is organized as follows. Section II briefly describes the characteristics of weak coherent pulses including photon number statistics and measurement technique. The design methodology of pulse laser module is illustrated in section III. In section IV, we present experimental results for pulse laser module along with WCP source. Finally, we conclude the paper and outline the future work in section V.

II. Weak coherent pulse Characteristics

A. Poissonian Photon Statistics

Weak coherent pulses follow Poissonian photon statistics, as shown in Eq. (1), characterized by its mean photon number, μ. Poisson distribution, as with any parameter $\mu > 0$ has nonzero probability for any given integer n. The probability to find n photons in such a coherent state:

$$P(n,\mu) = \frac{e^{-\mu}\,\mu^n}{n!} \tag{1}$$

Accordingly, the probability that a non-empty weak coherent pulse contains more than 1 photon,

$$P(n>1|n>0,\mu) = \frac{1-P(0,\mu)-P(1,\mu)}{1-P(0,\mu)} \cong \frac{\mu}{2} \tag{2}$$

For a weak coherent pulse, there is no way to create a single-photon pulse with certainty due to the probabilistic nature of the number of photons in a time interval. Therefore, the probabilities of emission of both multi-photon and single photon must be carefully optimized since they are highly correlated. The multiphoton emission is usually minimized by highly attenuating the optical pulses so that the average number of photons per pulse falls well below 1 [1]. This weak regime bounds the multi-photon to nonzero-photon emission ratio to μ/2 as per Eq. (2), at the cost of highly increasing the vacuum emission probability to ~1-μ. This greatly decreases the performance of a WCP source compared to a single photon source, as can be seen from Fig.1, which is a graphical outcome deduced from Eq. (1) for

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different values of n and μ. For μ close to 0.1 there is a probability that higher than 90% of the pulses contains no photons, effectively reducing the key rate below one tenth of the pulse repetition rate. The values of μ should be set below 0.1 so as to keep multiphoton events below a certain acceptable limit.

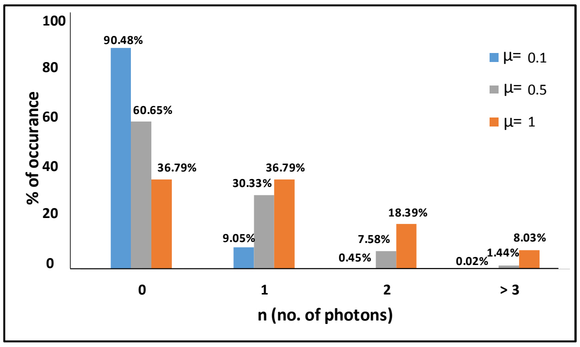


Fig. 1. Poisson statistics of weak coherent laser pulses

B. Second Order Coherence

In order to determine the quality of single photon source, second order correlation function or normalized intensity correlation $g^{(2)}[n]$ is computed by performing HBT experiment, where n take on integer values denoting pulse number. It gives information about emission probability of source's multi photon events. HBT set-up, as shown in Fig.2, consists of a 50:50 beam splitter, two single photon detectors (SPD) and time tagger or coincidence electronics. The SPDs count the number of photons transmitted through or reflected from the beam splitter. A series of measurements are performed in which the numbers n_1 and n_2 of photons counted by the two detectors during a brief time interval are recorded.

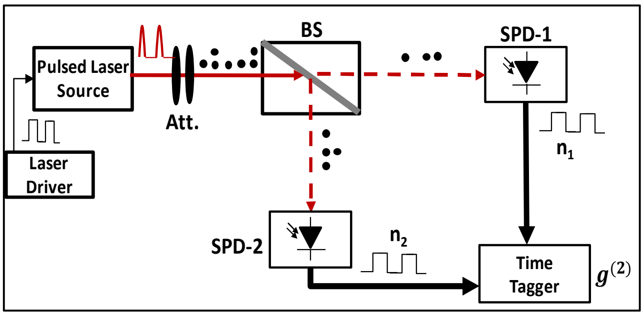


Fig. 2. HBT (Hanbury-Brown-Twiss) set-up for characterizing $g^2[n]$

$$g^{(2)} = \frac{\langle n_1 n_2 \rangle}{\langle n_1 \rangle \langle n_2 \rangle} \tag{3}$$

The numbers of counts in each detector in a single run are not however in general the same. In quantum sense, each incident photon either passes the beam splitter or is reflected from it. The average value $\langle n_1 n_2 \rangle$ of the product of counts in each single run, the correlation function, determines the extent to which coincident counts occur in the two detectors. The quantum analogue of second-order coherence is obtained by normalizing the second order correlation function, shown in Eq. (3). HBT interferometer works qualitatively for ideal single photon source, if only one photon at input port, there is no way for both detectors SPD-1 and SPD-2 to detect a photon simultaneously and hence $g^{(2)}[0] = 0$, where $g^{(2)}[0]$ is the autocorrelation of the pulse train of incoming photons. Theoretically, the second order coherence for a pulsed coherent source is $g^{(2)}[n] = 1$ for all n.

The photon probability distribution of a coherent pulse remains Poissonian even after attenuation, thus giving the distribution of WCP source as Poissonian only. The attenuation does not change the second order coherence. For WCP source, the autocorrelation of the pulse train can be closely approximated [7] as per Eq. (4).

$$g^{(2)}[n] \simeq \frac{N_c[n]}{R_A R_B T_{rep} T_{int}} \tag{4}$$

where N_c [n] is the number of correlation events recorded by the time tagger in the n^{th} histogram bin, R is the count rate on each detector T_{rep} is the repetition rate and T_{int} is the experiment run time.

III. Design of Pulse Laser Module

The block schematic of pulsed laser module is shown in Fig.3. It consists of a pulse driver circuit along with a TEC (Thermo-electric cooler) controller. The pulse driver is required to control the laser drive current as per the input TTL signal and the TEC controller is required to provide the wavelength & power stabilization over a temperature range.

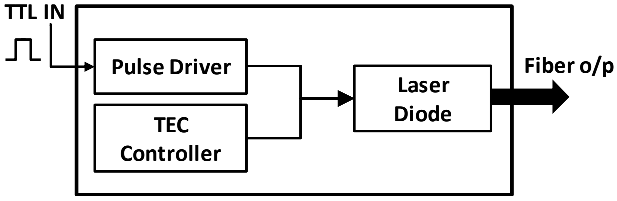


Fig. 3. Block schematic of Pulsed Laser Module

A. Pulse Driver

The laser pulses can be triggered by switching the operating voltage on and off. The power supply sends a certain current to laser diode when the switch is triggered, that causes certain optical power to be emitted. This switch can be a transistor or metal oxide semiconductor field effect transistor (MOSFET), depending on the required rise time and the pulse width of the emitted pulse.

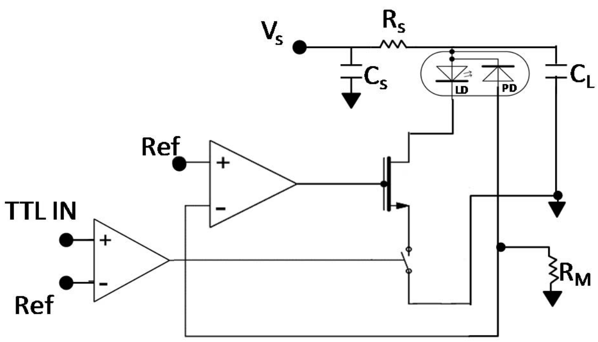


Fig. 4. Schematic of Pulsed laser driver

To meet the requirement of narrow pulse width of the order of ~5*ns* and high pulse repetition rate capabilities, integrated pulse driver [8] is used to drive a laser diode. This driver is capable of providing continuous wave operation and spike-free switching with defined current pulses of up to 100 *MHz* repetition rate. The schematic of pulse laser driver is shown in Fig.4. The optical output power of the laser diode is set-up by taking feedback from photo detector (integrated with laser diode package) and adjusting the external resistor, R_M. This is operated in automatic power control (APC) mode with TTL signal applied as a switching input.

B. TEC controller

The TEC controller circuit is designed to achieve the wavelength stabilization and to maintain the output power stability over temperature. It is a monolithic controller [9] that drives a TEC, inbuilt to laser diode, to stabilize its temperature. This device relies on a thermistor to sense the temperature of the laser diode attached to the TEC. The loop is controlled with high stability and low noise by a PID compensation network, as shown in Fig.5. The integrated TEC consist of two auto-zero amplifiers viz. Chop1 and Chop2. The Chop1 amplifier acts as a temperature measurement amplifier whereas the Chop2 amplifier acts as a PID compensation amplifier. The Chop1 amplifier amplifies the thermistor voltage and creates a voltage that is a function of the object temperature. The temperature of the laser diode is measured by a 10 kΩ thermistor mounted inside laser diode package and is fed back to the controller to correct the loop and settle the TEC to an appropriate final temperature. To linearize the non-linear resistance versus temperature characteristics of a thermistor for measurement over a wide temperature range, a resistor (R_Y) is added in series with the thermistor. The voltage output at Out1 can be expressed as

$$V_{out1} = \left(\frac{R_F}{R_{th} + R_Y} - \frac{R_F}{R_X} + 1\right) \times \frac{V_{ref}}{2} \qquad (5)$$

where, R_{th} is thermistor resistance, R_y is compensation resistor.

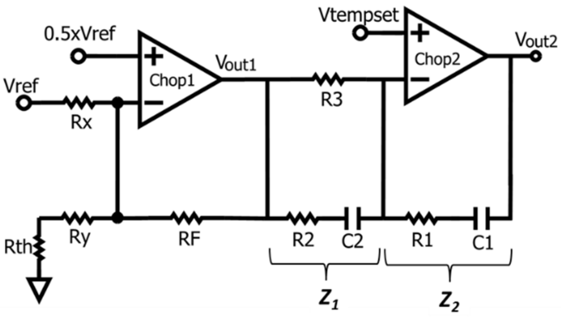


Fig. 5. Schematic of TEC controller circuit

The Chop2 amplifier compares the temperature measurement voltage, V_{out1}, against the target temperature set input voltage, $V_{tempset}$, creating an error voltage that is proportional to the difference. The target temperature is set with an analog input voltage with an external resistor divider. The voltage at Out2 can be expressed as

$$V_{out2} = V_{tempset} - \frac{Z_2}{Z_1}\left(V_{out1} - V_{tempset}\right) \qquad (6)$$

where Z_1 and Z_2 are the impedances of the PID control loop, described as,

$$Z_1(s) = R_3||(R_2 + \frac{1}{sC_2}) \qquad (7)$$

$$Z_2(s) = R_1 + \frac{1}{sC_1} \qquad (8)$$

The V_{out2} is then fed to the MOSFET gate driver, which is connected to external MOSFET devices. The appropriate current is then supplied to the TEC of laser diode through MOSFET to control the heat flow inside the laser diode package required to maintain its constant operating temperature. A 2.5 V voltage reference (*V*ref) is provided for the thermistor temperature sensing bridge.

A typical PID compensation network consists of a very low frequency pole and two separate zeros at higher frequencies. In this circuit, an additional pole is added at higher frequency than the zeros to reduce the noise sensitivity of the control loop. The transfer function of this PID controller can be expressed as

$$H(s) = \frac{K\,(1 + sR_1C_1)(1 + s(R_2 + R_3)C_2)}{s\,(1 + sR_2C_2)} \qquad (9)$$

where $K = 1/R_3C_1$. The bode plot for the gain of H(s) is shown in Fig.6. The unity-gain crossover frequency of the transfer function can be expressed as

$$f_{0(Hz)} = 1/(2\pi\, R_3C_1) \qquad (10)$$

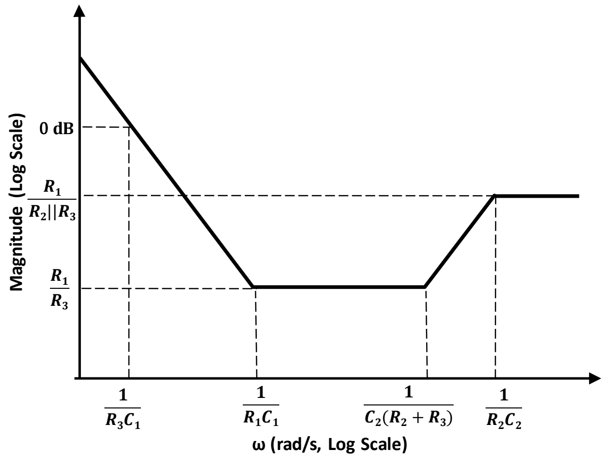


Fig. 6. Bode plot for PID controller

IV. Experimental Results

The semiconductor laser diode with wavelength of 785nm is chosen for the development of integrated pulse laser module based on the availability of the highly efficient single photon detectors. A miniaturized PCB incorporating both pulse driver and TEC control circuitry is designed and developed. The input signal to this module is digital TTL pulses with desired pulse width and repetition rate, which triggers the laser diode to generate coherent optical pulses with pulse width as low as 5*ns* and repetition rate as high as 100 *MHz*. The resistors and capacitors values of PID compensation network is optimized to minimize the temperature settling time of laser diode.

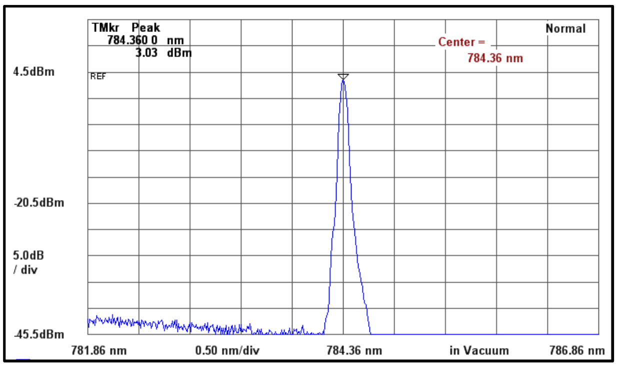


Fig. 7. Measured optical spectrum of pulsed laser diode

The wavelength spectrum of output of laser diode is shown in Fig.7. The measured wavelength is 784.36 *nm* with output power of +3.0 *dBm*. The output of the pulse laser module is coupled with polarization maintaining (PM) fiber. The generated beam is linearly polarized with ellipticity of <2° and degree of polarization ~100%, measured with polarimeter as shown in Fig.8. This module is tested with input TTL pulses of different repetition rate and pulse widths, resulted in intensity modulated signal. This modulated optical signal is analyzed by a visible photodetector which converts the optical signal back into electrical domain. Fig.9 shows the measured oscilloscope plot for 10 *MHz*-10 *ns* and 100 *MHz*-5 *ns* pulse triggering.

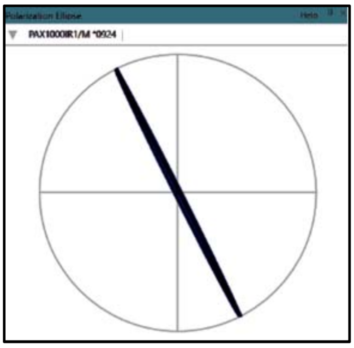


Fig. 8. Measured polarization ellipse of pulsed laser module

The optical attenuation level to reach single photon level is determined as follows: The optical output power (Pavg) of pulsed laser module is -5*dBm* with pulse repetition rate of 10 *MHz*. The power Pavg can be represented as

$$P_{avg} = N\,h\,\nu\,f \tag{11}$$

where *N* is the number of photon per pulse, h is the Planck's constant (6.634 x 10^{-34} J.s), ν is the frequency (*Hz*) of the emitted photon and f is the pulse repetition rate (*Hz*). The number of photon per pulse,

$$N = \frac{P_{avg}}{P_{single}} \tag{12}$$

The attenuation level for single photon generation (μ=1),

$$\alpha = \frac{1}{N} = \frac{P_{single}}{P_{avg}} \tag{13}$$

In order to have 1 photon in every 10 pulses (μ=0.1),

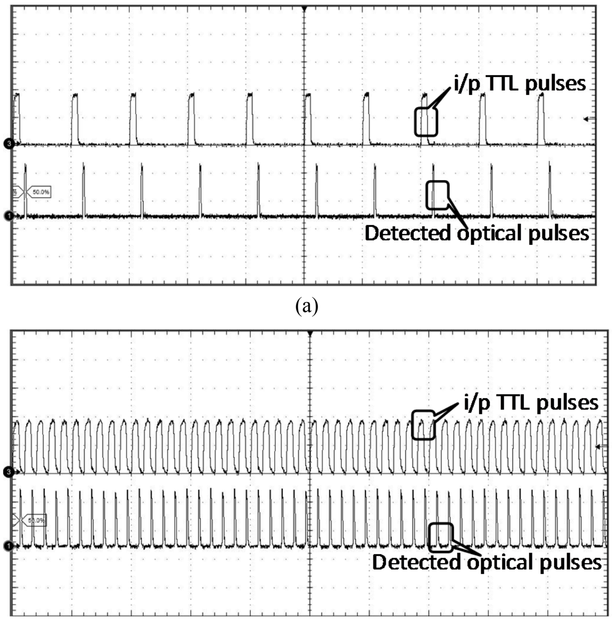
$$\alpha_{0.1} = \frac{0.1}{N} \tag{14}$$

The average power of a single photon generated at a repetition rate of f,

$$P_{single} = h\,\nu\,f \;\simeq\; -85.9\,dBm$$

Therefore, the number of photon in a pulse according to Eq. (12) is N = 1.25 x 10^{8} for Pavg of -5 *dBm*. Hence, the attenuation level required to have one photon per pulse (μ=1) is -80.9 *dB* as per Eq. (13). To ensure only single photon generation with extremely low multiphoton emission μ is set to 0.1, which give the attenuation level of -90.9 *dB*.

The laboratory set-up for test and characterization of $g^{(2)}[n]$ is same as shown in Fig.2. The SPDs, with detection efficiency ~70% and dark counts <100 counts per sec (*cps*) were used for single photon detection. The measured average value for $g^{(2)}[0]$ is ~0.98, which is very close to the theoretical value as shown in Fig.10. The difference between successive pulse number, n^{th} and n^{th}+1, is the pulse repetition rate (T_{rep}). The count rate of 3.15 *Mcps* per SPD is measured during HBT experiment for 100 *MHz* pulse triggering. It corresponds to 10 *Mcps* count rate at the output of WCP source. The photon count rate calculation is based on various parameters such as beam splitter efficiency (50%), mean photon no. (10%), SPD efficiency (70%), coupling efficiency (90%) etc. These results show that the developed WCP source follows Poissonian statistics which indicates source has good quality. The various targeted and measured parameters for this WCP source are tabulated in Table.1. The fully assembled mechanical package of pulse laser module is shown in Fig. 11.



(b)

Fig. 9. Measured results for (a) 10 *MHz*, 10*ns* (b) 100 *MHz*, 5*ns* pulse triggering

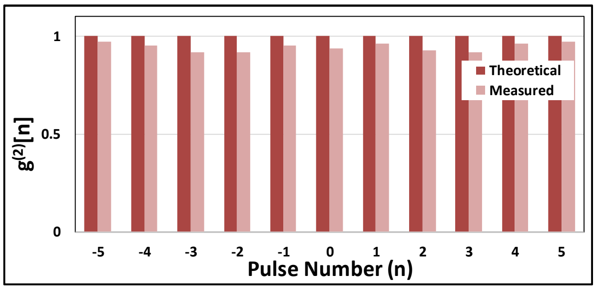


Fig. 10. Second order coherence for WCP source

TABLE I. MEASURED PARAMETERS OF WCP SOURCE

Sr.	Parameters	Targeted specs.	Measured Values
1.	Wavelength	785 *nm*	784.36 *nm*
2.	Mean Photon No. (μ)	~0.1	0.11
3.	Single photon count rate	upto10 *Mcps*	upto10 *Mcps*
4.	Second order coherence	~1	0.98
5.	Ellipticity	<5°	~2°
6.	Degree of polarization (DOP)	100%	~100%
7.	Input data signal level	LVTTL	LVTTL
8.	Input data Interface	SMA	SMA
9.	Output interface	Free space	Free space
10.	Power consumption	< 2 W	1W (max.)

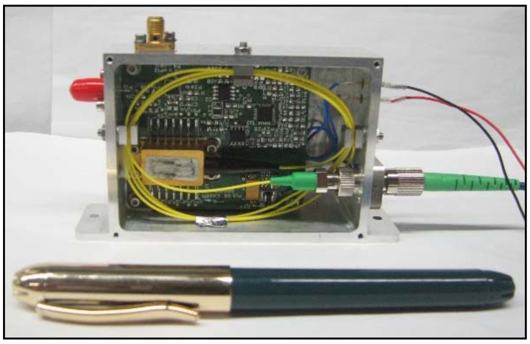


Fig. 11. Assembled pulse laser Module

V. CONCLUSION

A design methodology to develop WCP source based on attenuated laser pulses was proposed and experimentally demonstrated. A miniaturized pulse laser module was designed for generating coherent optical pulses with narrow pulse width and high repetition rate of upto 100 *MHz*. These optical pulses were attenuated to provide mean photon number per pulse ~0.1. The generated single photon stream was linearly polarized with high single photon count rate of ~10 *Mcps*. The second order coherence, $g^2[0]$, value of ~0.98 was calculated by performing HBT experiment, validates the quality of this source. This shows that our proposed methodology lead to the design & development of a WCP source with good quality and high photon count rate. In future, this source will be used to develop an end-to-end QKD system to achieve unconditionally secure communication.

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REFERENCES

[1] N. Gisin, G. Ribordy, W. Tittel and H. Zbinden, "Quantum cryptography," *Review Modern Physics,* vol. 74, pp. 145-195, 2002.

[2] G. Brassard, N. Lutkenhaus, T. Mor and B. C. Sanders, "Limitations on Practical Quantum Cryptography," *Physical Review Letters,* vol. 85, no. 6, pp. 1330-1333, 2000.

[3] M. D. Eisaman, J. Fan, A. Migdall and S. V. Polyakov, "Invited Review Article: Single-photon sources and detectors," in *Review of Scientific Instruments*, 2011.

[4] E. Diamanti, H. K. Lo, B. Qi and Z. Yuan, "Practical challenges in quantum key distribution," *npj Quantum Inf.* 2, 16025, 2016.

[5] F. Xu et al., "Experimental quantum fingerprinting with weak coherent pulses," *Nature Communications,* vol. 6, no. 8735, 2015.

[6] L. Giannelli, T. Schmit and G. Morigi, "Weak coherent pulses for single-photon quantum memories," *Physica Scripta,* vol. 94, no.1, 2018.

[7] A. Migdall, S. V. Polyakov, J. Fan and J. C. Bienfang, Single-photon generation and detection, vol. 45, Academic Press, 2013, pp. 32-52.

[8] iC-Haus, "N-type laser diode driver-iC-NZN, datasheet", Rev. D1, 2018.

[9] Analog Devices, "Thermoelectric cooler (TEC) controller-ADN8831," *datasheet,* Rev. 0 ed., 2005.